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Effect of Two Different Irrigation Strategies on the Yield Components of Five Rice Varieties in a Cold Mediterranean climate in the South-Central Zone of Chile

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Abstract

Rice is one of the agricultural species that consumes a lot of water. In countries with cold climates such as Chile, a 200 mm high sheet of water is used to cope with night temperatures below 10 °C. This practice consumes 18,000 m^3 ha^{-1} of water per season. Climate change is currently a major problem, where the reduction in precipitation can exceed 40%. Under this context, the current rice production system is unsustainable. The objective of the research seeks to evaluate five rice varieties with different lengths of the productive cycle, under two water management strategies (intermittent vs. traditional irrigation), evaluating the yield components of rice varieties. The trial was conducted in the Mediterranean climate of South-Central Chile, zone is characterized by low temperatures. The traditional commercial variety used was Zafiro (*Oryza sativa* sp. japonica), which showed good yields under flood irrigation conditions with 8,100 and 7,300 kg/ha for both seasons, respectively. However, under intermittent irrigation conditions, it showed a drastic yield reduction of 94 and 42% for both seasons, respectively. While the short-cycle variety MA042, showed yields of 12,663 and 11,063 kg/ha under flood irrigation strategy for both seasons, while under AWD system it showed only 34 and 4% reduction, respectively. The use of short cycle varieties, which require less water and are more tolerant to low temperatures, represent a productive option for rice farmers in cold climates, where water resources are an increasingly scarce commodity.

Keywords: rice production, Alternate Wilting Drying (AWD), yield components, Continuous Flooding (CF), climate change

1. Introduction

Rice is one of the most consumed cereals in the world (Yang et al., 2017). According to the latest international report provided by the USDA, world rice production is currently 473 million tons, and it is expected that by 2035 a production of 555 million tons will be needed to supply demand (Gadal et al., 2019). Unfortunately, rice is one of the crops that consumes the most water for its production (Cabangon et al., 2004; Kumar et al., 2014). In most of the world, rice is managed under irrigation conditions, where the plant is immersed in water (Belder et al., 2004; Shao et al., 2014) with a sheet of approximately 50-100 mm of water (Bouman & Tuong, 2001; Bocchiola, 2015). In Chile, due to the low night temperatures, it is grown with sheets of up to 200-250 mm in high to generate a buffer effect that avoids the negative effect of low temperature. Approximately 75% of the world's rice area is produced under irrigation (Yang et al., 2017). However, a smaller percentage receives rainwater during its productive period (Belder et al., 2007). This is because rice needs a large amount of water for its correct productive and physiological development (Shao et al., 2014; Bocchiola, 2015). This creates problems for several reasons, one of them is soil fatigue and accumulation of Fe^{2+} which in the long term significantly reduces the yield and productive capacity of the soil (Bhushan et al., 2004). On the other hand, the main rice producing areas of the world are suffering the negative effects of climate change (Tabbal et al., 2002; Bocchiola, 2015). For example, in Asia, which has more than 18 million hectares dedicated to its production, there has been a reduction in the availability of water resources between 40 to 60% (Bhushan et al., 2004). Chile suffers the same situation, showing a considerable reduction in its rainfall in recent years (IPCC, 2019). This situation forces farmers to look for new productive alternatives for this crop, which are more sustainable and friendly to the environment (Yang et al., 2017) and which allow considerable water savings without significantly affecting the final yield of this crop (Tabbal et al., 2002; Bhushan et al., 2004, Bocchiola, 2015).

Currently, there are several irrigation systems that allow significant water savings in this crop (Kumar et al., 2014), these systems seek an alternation between moments of immersion and non-immersion in water (ASNS) (Bouman & Tuong, 2001; Tabbal et al., 2002; Belder et al., 2004; Cabangon et al., 2004). Among these systems we can find continuous soil saturation (CS), direct seeding (dry) (DS) (Bouman et al., 2005; Matsuo & Mochizuki, 2009), rice intensification system (RIS) (Geethalakshmi et al., 2009) and Alternate Wetting and Drying irrigation system (AWD) (Belder et al., 2004; Cabangon et al., 2004; Geethalakshmi et al., 2009; Sun et al., 2012; Liu et al., 2013). In the latter system, once the visible water layer disappears, water is quickly reincorporated until it reaches (Yao et al., 2012) about 50 mm in height, according to the producer's criteria (Rejesus et al., 2011).

Literature reports contradictory results when using this type of irrigation systems, showing that they depend on factors such as the climate, the time and amount of water applied, the variety evaluated and the duration of the period without water (Bouman & Tuong, 2001; Belder et al., 2004). In the case of traditional rice varieties, that is, long-cycle varieties, the lack of water or prolonged periods of drought, could cause a significant reduction in leaf production, increased stomatal closure, and decreased photosynthetic capacity of the plant, reducing the plant size, increasing the floral abortion and the grain sterility, reducing its final weight (Bouman & Tuong, 2001; Tuong et al., 2005). Currently, a series of new varieties more tolerant to lack of water and low temperature (< 10 ºC) are being worked on, but they have not been shown to have the same productive potential (Bouman et al., 2005). However, according to some studies, these varieties have shown a better adoption to irrigation systems that use less water (Yao et al., 2012; Liu et al., 2013), due to the fact that they have a shorter vegetative cycle (early vegetative vigor and early and uniform emergence) and can function under aerobic conditions (Sandhu et al., 2019). Likewise, these varieties have a greater tolerance to low night temperatures during reproductive periods, which is detrimental to the final rice yield, due to the increase in grain sterility (Gombos et al., 2008).

Regarding studies carried out at the field level, the results are diverse depending on the place and climatic conditions where they were carried out (Yang et al., 2017). In subtropical climates such as China, Belder et al. (2004) conducted an experiment in the Tuanline region, comparing a traditional irrigation system versus AWD. In this regard, they did not observe statistical differences in biomass production, yield and yield component, achieving water savings between 6 to 14% in the total volume applied. Similarly, Cabangon et al. (2004), in a study carried out in the same region of Tuanline, did not observe differences in biomass production and grain yield, when purchasing a continuous flood system (CF), compared to AWD, achieving water savings between 92 and 76 mm for each zone respectively, which would translate into 10% water saving. On the other hand, Liu et al. (2013) in a study carried out with two super varieties of rice at Yangzhou University, compared the CF system and the AWD, combining different nitrogen application methods, they found that the combinations of AWD with site-specific nitrogen application methods, the photosynthetic rate and the accumulation of dry matter would increase, generating an increase in the final yield (Sun et al., 2012; Yang et al., 2017). Similarly, in tropical climates such as the Philippines, Bouman et al. (2005), compared aerobic irrigation conditions (irrigation from a soil tension of 30 kPa at 15 cm depth) (Matsuo & Mochizuki, 2009) versus traditional flood irrigation, on lowland farms, they saw yield declines from 22 to 32%, but with water savings from 27 to 51%.

In climates like Chilean, that is, temperate with low night temperatures, the results are different from those observed previously. Sandhu et al. (2019) in a study carried out simultaneously in the Philippines, India, Bangladesh, and Nepal, they observed that early growing varieties with greater length and density of root hairs; earlier and more uniform emergence; and higher grain yield under a direct sowing system (varieties with shorter production cycles), showed to be more tolerant to aerobic conditions (lack of water), obtaining higher yields than traditional varieties. Jancsó et al. (2007) obtained similar results in temperate Hungarian climates, observing that some varieties of Hungarian origin with shorter cycles, showed a good tolerance to night cold (Tº < 10 ºC) and lack of water. However, they highlighted the need for continuous evaluations during the season, especially in temperate climates, due to the duration of the cold and changes in the photoperiod during the reproductive period of rice.

Although the use of AWD is presented as an interesting alternative for growing rice in areas with water scarcity (Oliver et al., 2019). However, it is essential to carry out constant evaluations of the productive variables, especially in Mediterranean climates, due to the duration of the cold and changes in the photoperiod (Jancsó et al., 2017). This information becomes especially important under Chilean production conditions, where night temperatures below 10 °C are observed during the reproductive rice period, which could be decisive in the final yield of this crop (Ortega, 2007). Based on the above, the objective of this study is to evaluate two irrigation systems (conventional vs AWD) in five rice varieties, on the yield components in a cold Mediterranean climate, determining if the short-cycle varieties are more tolerant than traditional varieties (Zafiro), under a strategy of saving water and climatic conditions of low temperatures registered in the rice-growing zone of Chile.

2. Materials and Methods

2.1 Experimental Site Description

The study was carried out in the experimental field of Los Castaños, El Almendro farm, in the Retiro locality, Maule region, Chile (35°57′S; 71°47′ W; 554 m.a.s.l). The experimental site has a Cold Mediterranean climate with a prolonged dry season that extends between November and March of each year, due to this reason, a water supply is essential throughout the growing season of the crop. Average temperature for winter and summer are 8 °C and 22.2 °C, respectively. Average annual rainfall is 1150 mm. The experimental work was sown during the month of November, that is, a late sowing, this to observe the behavior of the varieties evaluated during the low temperatures in the reproductive state (primordial beginning, microsporogenesis and flowering) during the months of February and March. Soil preparation was carried out with a chemical fallow, with a disc scrape at 20 cm depth and the soil was leveled to zero with a laser leveling. Weed control was carried out with pre-emergent chemicals in rice, Glyphosate, Clomazone and Pendimetahalin 7 days after the first irrigation before the rice emerged, then florpirauxifene-benzyl with post-emergence tiller initiation rice. The sowing was dry with a seeder machine at a depth of 2-2.5 cm together with a standard fertilization of Nitrogen, Phosphorus and Potassium.

The soil corresponds to the Quella series, soils in a low position of the depositional plane (lacustrine), originating from volcanic tuff, a clay loam surface texture and a very dark grayish-brown color, a clay texture (dense) and a dark color in the depth. Soils with flat topography, slow permeability, imperfect drainage and very slow surface runoff (Table 1). For the climatic characterization of the experimental site, an automatic weather station (Adcon Telemetry, model A730, Klosterneuburg) was used to record basic climatic variable of temperature in 1-hour intervals (Figure 1).

Table 1. Soil characteristics of the experimental site

Sand (%)	Silt (%)	Loam (%)	pH	C.E. dS/m
54	22	24	5.23	0.108

2.2 Description of Plant Material Used and Experimental Design

For the trial, two irrigation treatments were evaluated, which were Improved Permanent Flood (IPF) (maintenance of the water sheet throughout the phenological development of the rice, maintaining the height of water, entering water only to maintain the sheet) and Alternate Wetting and Drying irrigation system (AWD) (intermittent application of a sheet 5 cm net, each time the water level reaches field capacity, until the tillering period). Each main plot was separated by compacted 40 × 40-centimeter parapets, with individual water inlet and outlet, water inlet and outlet pipes.

In each of these systems, 5 rice varieties (*Oryza sativa* sp. Japonica) were evaluated: Zafiro variety was used as a control (the most used variety in Chile) and was compared with other four varieties, ALM 103, ALM 107, MA042 and ALM112. A productive frame with an area of 5 × 3 m (experimental unit) was considered, which was replicated three times in a completely random design. Flowmeters were installed in both irrigation treatments, which allowed determining the water consumption for each one of the systems. Immediately after sowing the first irrigation was given to hydrate and stimulate germination. This process was carried out 24 hours later and a third time after 7 days, ending the process when the plant reached the third leaf. After this the irrigation treatments were established.

2.3 Plant Measurements

To characterize the components of rice yield, the weight of 1000 grains (g), percentage of flowers sterility (%), number of total grains per panicle, number of vain grains per panicle, number of large filled per panicle, number of panicles per 0.5 square meter per repetition were measured. Finally, with these variables the field yield (kg/ha) was determined.

The number of panicles was determined in the R7 growth stage (pasty state) since their differentiation is more certain (Counce et al., 2000). The rest of the variables were determined in the R9 stage (senescence) in each of the experimental plots.

2.4 Statistical Analysis

An analysis of variance (ANOVA) was carried out using the R software, to evaluate statistical differences between each evaluated treatments, that is, between varieties and between types of irrigation by variety. For the separation of means, the Tukey mean comparison test was used, with a value of $p < 0.05$. For the homogeneity of the data, the Levenne test with value of $p > 0.05$ was used.

In turn, a Principal Component Analysis (PCA) was performed with all the variables and treatments evaluated, to observe the correlations between the variables and the data. The XLSTAT Pearson Edition (2021) software was used to perform this analysis.

3. Results and Discussion

3.1 Climatic and Biological Cycles Analysis

During the 2017-2018 season, minimum temperatures fluctuated around 10 °C, with a reduction as of February 20, 2018 (Figure 1). In turn, the rains were abundant in early November (around 20 mm) and mid-March (more than 25 mm in specific events), which constituted a problem for the planting and harvesting of rice, respectively. Especially considering late sowing dates due to different productive factors, which was simulated under the conditions of this trial. In the case of the 2018-2019 season, the scenario was even more complex, with minimum temperatures around 5 °C during much of the reproductive period of rice. While in the case of the rains these were less than the previous season, complicating the sowing and harvesting tasks. This was mainly due to the El Niño-Southern Oscillation (ENSO) phenomenon, which brought with it a considerable decrease in rainfall and an increase in extreme minimum temperatures (Figure 1).

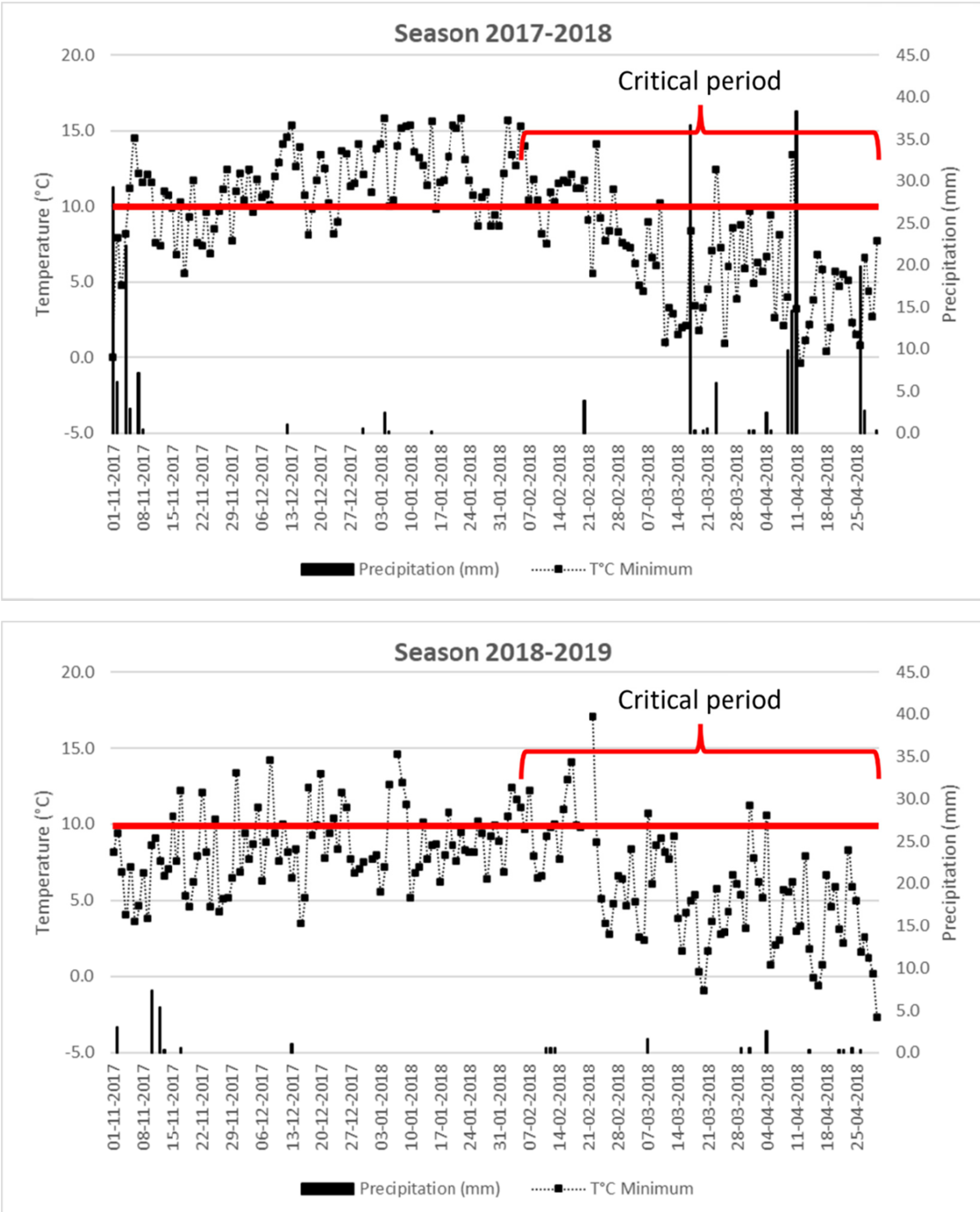


Figure 1. Summary of climatic data registered at the experimental site in two seasons (2017-2018 and 2018-2019 (minimum temperature (T; °Celsius) and precipitation (pp; mm)). The horizontal red line represents the complex thermal threshold for the reproductive period of rice (10 °C). The red bracket highlights the critical period in which the reduction in temperatures is observed

Of the 5 varieties used in the experiment, two have a short growth cycle, one an intermediate cycle and two a long cycle, which affects the total number of days between sowing and harvest and the time when 50% of the flowering occurs (Table 2). The short-cycle varieties (ALM 103 and MA042) reach 50% flowering during the first 2 weeks of February, that is, between 70 and 89 days after sowing. For its part, variety 112 of intermediate cycle reaches this phenological period between the last week of February and the first week of March (between 83 and 97 days after sowing). While long-cycle varieties reach this phenological stage between the first and last week of March, that is, between 99 to 114 days after sowing. Regardless of the irrigation system used or the season evaluated (Table 2). It should be noted that the sowing date of the trial was late, in order that the reproductive period was in the months of February and March, that is, when the minimum temperatures usually drop drastically.

Table 2. Biological cycle information recorded in the experimental site during two seasons 2017-2018 (first), 2018-2019 (second). This analysis corresponds to the total or average values of each variable by date range analyzed

Season	Irrigation	Variety	Date 50% flowering	Number days sowing to flowering	Number days emergency to flowering	Phenological cycle	Amount of water applied (m^3/ha)
2017-2018	AWD	Zafiro	16-03-2018	114	102	Long	6,378
		ALM 103	08-02-2018	78	66	Short	3,961
		ALM 107	19-03-2018	117	105	Long	6,483
		MA042	13-02-2018	83	71	Short	4,592
		ALM 112	13-03-2018	93	81	Intermediate	5,486
	PF	Zafiro	01-03-2018	99	87	Long	9,460
		ALM 103	08-02-2018	78	76	Short	5,731
		ALM 107	01-03-2018	99	87	Long	9,460
		MA042	13-02-2018	83	71	Short	6,957
		ALM 112	23-02-2018	83	71	Intermediate	6,957
2018-2019	AWD	Zafiro	16-03-2019	113	102	Long	10,643
		ALM 103	13-02-2019	82	71	Short	6,111
		ALM 107	07-03-2019	104	93	Long	8,273
		MA042	20-02-2019	89	78	Short	7,317
		ALM 112	28-02-2019	97	86	Intermediate	7,787
	PF	Zafiro	04-03-2019	102	91	Long	13,295
		ALM 103	01-02-2019	70	59	Short	8,658
		ALM 107	27-02-2019	96	85	Long	9,973
		MA042	12-02-2019	81	70	Short	9,291
		ALM 112	14-02-2019	83	72	Intermediate	9,697

3.2 Principal Component Analysis (PCA)

To study the behavior of the evaluated variables and their correlation, a Principal Component Analysis (PCA) was performed. For the 2017-2018 season, axes F1 and F2 account for 71.32% and 19.93% of the total variance of the data, respectively, while for the 2018-2019 season, the same axes explain 59.5% and 21.52% of the total variance of the data. Together, both axes account for 89.25% and 81.02% of the total variability in the data for each season, respectively (Figures 2 and 3). In both seasons, the F1 axis of the analysis correlates mainly with the variables of number of filled grains/panicle, numbers of grains/panicle and yield per unit area (kg/ha), which show a direct correlation between them. Likewise, this axis is composed of the sterility percentage and number of vanes grains/panicle variables, which show a strong inverse correlation with the three variables mentioned initially. This relationship shows that a higher number of filled grains /panicle would imply a lower number of vane grains per panicle, thus increasing the final yield per unit area.

Under the same analysis, traditional cycle varieties such as Zafiro and ALM 107 show a higher correlation with the variables that decrease yield, *i.e.*, number of vane grains/panicle and percentage of grains sterility, showing that they are highly sensitive to low temperatures (10°C), so it is key to maintain a high-water level (15 - 20 cm) to ensure adequate yield (Figures 2 and 3).

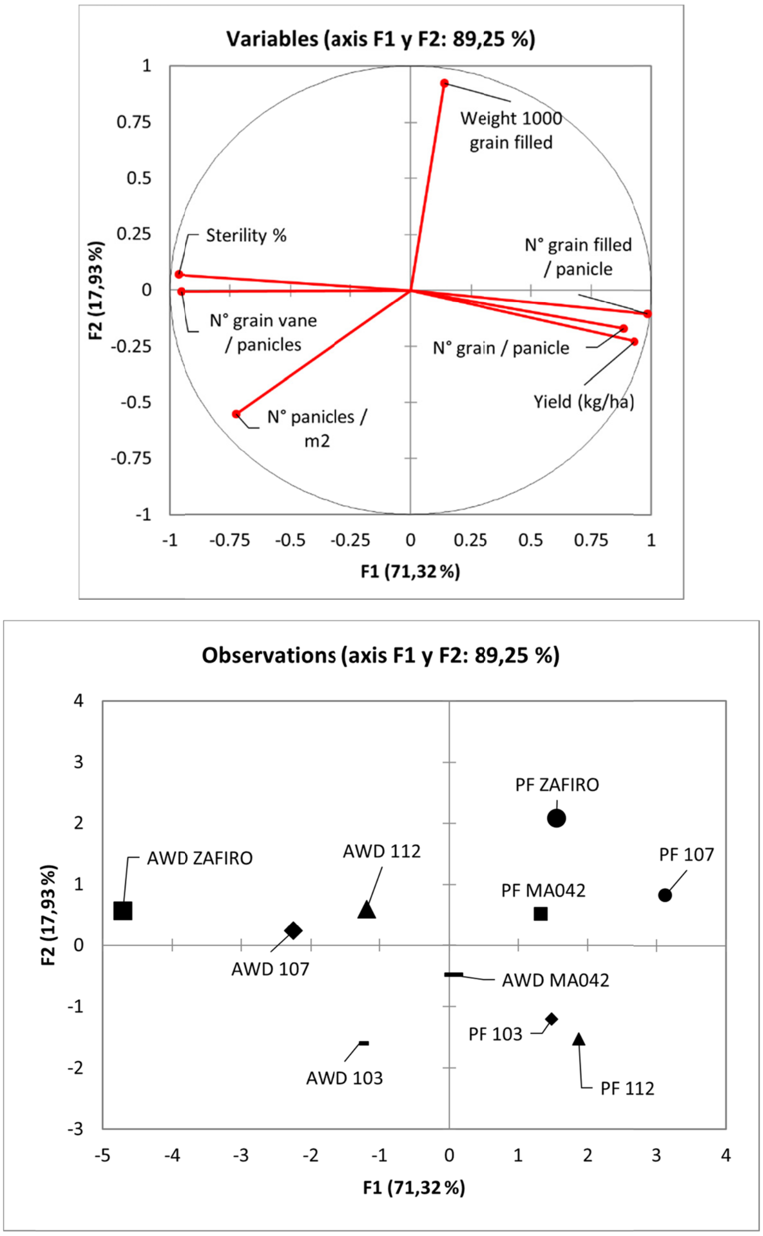
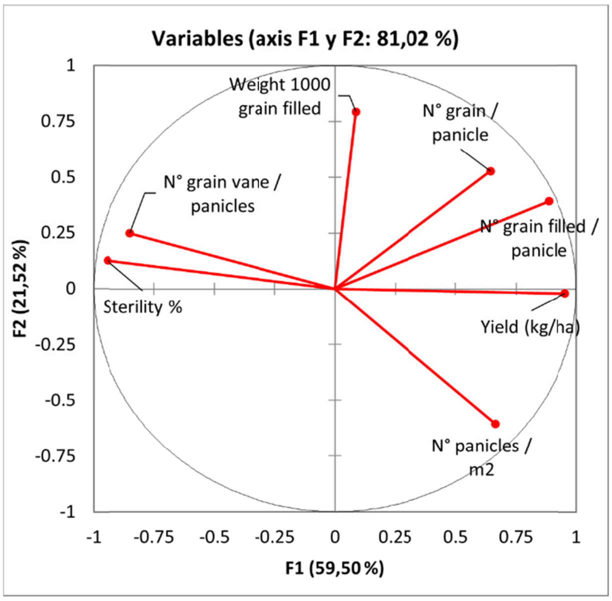


Figure 2. Principal Component Analysis (ACP) for the 2017-2018 season of 5 rice varieties (Zafiro, ALM 103, ALM 107, ALM 112 and MA042) subjected to two irrigation strategies (Alternate Wetting and Drying irrigation system (AWD) and Permanent Flooding system (PF))



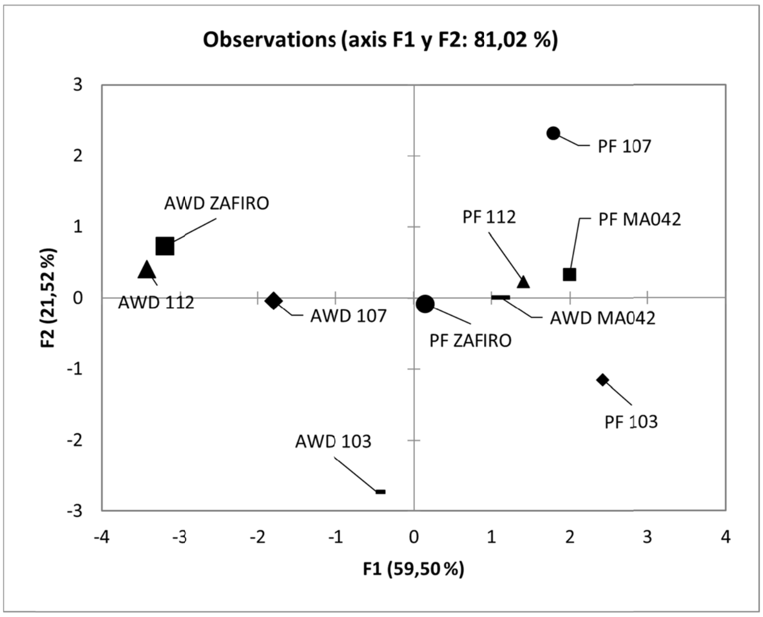


Figure 3. Principal Component Analysis (ACP) for the 2018-2019 season of 5 rice varieties (Zafiro, ALM 103, ALM 107, ALM 112 and MA042) subjected to two irrigation strategies (Alternate Wetting and Drying irrigation system (AWD) and Permanent Flooding system (PF))

3.3 Comparison Between Varieties Subjected to the Same Irrigation Strategy

In the case of the AWD irrigation system, statistical differences were observed in almost all variables for the two study seasons, except for the variable number of panicles/m^2 and numbers of full grains/panicle, respectively (Table 3). Under this irrigation system, the short-cycle variety MA042 presented the highest values, reaching yields of 8,346 and 10,579 kg/ha, for seasons 1 and 2, respectively. Same behavior shows ALM 103 reaching yield of 5,384 and 8,711 kg/ha for two seasons, respectively. While the traditional long-cycle variety Zafiro had the lowest values, with yields of 474 and 4,255 kg/ha for seasons 1 and 2, respectively. This behavior is mainly explained by the low number of full grains observed in the Zafiro variety, which has its reproductive period at the end of February and beginning of March, which is why it is highly affected by low temperatures.

For the PF irrigation system, the results are variable. During the 2017-2018 season, the intermediate cycle variety 112 achieved the highest yield in the trial with 15,623 kg/ha, while the Zafiro variety had the lowest yield with 8,128 kg/ha. In the variables of number of panicles/m^2 and numbers of full grains/panicle, Zafiro was inferior to the rest of the varieties evaluated but was superior in the weight of the 1000 grains variable. Zafiro, being a long-cycle variety, has more time to develop and accumulate more dry matter in the grain, which helps to increase its weight, this compared to the rest of the varieties evaluated. During the second season (2018-2019), statistical differences were only observed in the number of panicles/m^2 and the number of filled grains/panicle, with variety 107 and Zafiro being the lowest, respectively.

Table 3. ANOVA of difference in yield components (Number panicles/m^2 and Number filled grains), in five rice varieties, subjected to two irrigation strategies (Alternate Wetting and Drying (AWD) and Permanent Flooding (PF)), in two field measurement seasons (2017-2018 and 2018-2019)

Variety	AWD				PF			
	Yield (Kg/ha)	No. of Panicles/m^2	No. filled grain/panicle	Weight 1000 grain filled (gr)	Yield (Kg/ha)	No. of Panicles/m^2	No. filled grain/panicle	Weight 1000 grain filled (gr)
Season I (2017-2018)								
Zafiro	474a	915	8.3a	33.4b	8128a	431a	63.3ab	35.1b
ALM 103	5384b	686	41.8cd	27.4a	12393ab	764ab	72.4ab	29.6a
ALM 107	3690b	520	28b	31.9b	14185b	778ab	88.6c	34.2b
MAO42	8346c	679	51.6d	30.3ab	12663ab	694ab	62.7a	33.89b
ALM 112	4856b	644	36bc	31.9b	15623b	771b	77.8bc	30.2a
SD	*	n.s.	*	*	*	*	*	*
Season II (2018-2019)								
Zafiro	4255a	503ab	33.3	31.5c	7379	784ab	37a	30.9
ALM 103	8711ab	879c	43.7	24.8a	8723	912b	49.05ab	27.5
ALM 107	5611ab	471a	52	28.3b	10324	592a	66.0b	30.6
MAO42	10579b	748bc	52	29bc	11063	868b	48.5ab	31.4
ALM 112	6300ab	673abc	41	28.7bc	8861	796ab	49.38ab	31
SD	*	*	n.s.	*	n.s.	*	*	n.s.

Note. Different letters between dates indicate statistical differences (SD) between means (Tukey, $P \leq 0.05$) by season; *: significance $p < 0.05$, n.s.: no significance.

3.4 Comparison of the Behavior of Five Varieties Subjected to PF and AWD Irrigation Systems

Zafiro is a long-cycle variety with a high yield potential under flood irrigation system and high industrial quality. Under the PF strategy, it presented yields of 8,128 and 7,379 kg/ha, during the first and second season, respectively. While for AWD it obtained a yield of 479 and 4,255 kg/ha, *i.e.*, a reduction of 94 and 42% with respect to the PF strategy for the first and second seasons, respectively (Table 4).

MA042 is a short-cycle variety, with greater tolerance to water deficit. Under the PF treatment, it presented yields of 12,663 and 11,063 kg/ha, during the first and second seasons of the study, respectively. While for AWD it obtained a yield of 8,346 and 10,579 kg/ha, *i.e.*, a reduction of 34 and 4% with respect to the PF strategy for the first and second seasons, respectively (Table 4). It is important to note that although it performs well in AWD, it is a strain susceptible to tension, due to the lack of water.

ALM 103 is a short-cycle variety. Under the PF treatment, it presented yields of 12,393 and 8,723 kg/ha, during the first and second seasons, respectively. While for AWD it obtained a yield of 5,348 and 8,711 kg/ha, *i.e.*, a reduction of 56 and 0.1% with respect to the PF strategy for the first and second season, respectively (Table 4).

ALM 107 is a long-cycle variety with susceptibility to low temperatures. Under the PF treatment, it presented a yield of 14,185 and 10,324 kg/ha, during the first and second seasons, respectively. While for AWD it obtained a yield of 3,690 and 5,611 kg/ha, *i.e.*, a reduction of 74 and 46% with respect to the PF strategy for the first and second season, respectively (Table 4).

ALM 112 is an intermediate-cycle variety. Under the PF treatment, it presented a yield of 15,623 and 8,861 kg/ha, during the first and second seasons, respectively. While for AWD it obtained a yield of 4,865 and 6,300 kg/ha, *i.e.*, a reduction of 68 and 30% with respect to the PF strategy for the first and second season, respectively (Table 4).

Table 4. ANOVA of the effect of two irrigation strategies (Alternate Wetting and Drying (AWD) and Permanent Flooding (PF)), on yield components (Number panicles/m^2 and Number filled grains, filled grains weight (gr) in five rice varieties for two field measurement seasons (2017-2018 and 2018-2019)

Variety	Yield (kg/ha)			Number of Panicles/m^2			Number filled grain/panicle			Weight 1000 grain filled (gr)		
	AWD	PF	SD	AWD	PF	SD	AWD	PF	SD	AWD	PF	SD
Season I (2017-2018)												
Zafiro	474a	8,128b	*	915a	431b	*	8.3a	63.3b	*	33.4	35.1	n.s
ALM 103	5384a	12,393b	*	686	764	n.s.	41.8a	72.4b	*	27.4	29.6	n.s
ALM 107	3690a	14,185b	*	520	778	n.s.	28a	88.6b	*	31.9	34.2	n.s
MAO42	8346a	12,663b	*	679	694	n.s.	51.6a	62.7b	*	30.3a	33.8b	*
ALM 112	4856a	15,623b	*	644	771	n.s.	36.0a	77.8b	*	31.9a	30.2b	*
Season II (2018-2019)												
Zafiro	4255a	7379b	*	503a	784b	*	33.3a	37b	*	31.5	30.9	n.s
ALM 103	8711	8723	n.s	879	912	n.s.	43.7a	49.05b	*	24.8a	27.5b	*
ALM 107	5611a	10324b	*	471a	592b	*	52a	66.0b	*	28.3	30.6	n.s
MAO42	10579a	11063b	*	748a	868b	*	52	48.5	n.s.	29	31.4	n.s
ALM 112	6300a	8861b	*	673a	796b	*	41a	49.38b	*	28.7	31	n.s

Note. Different letters within dates indicate statistical differences (SD) between means (Tukey, P ≤ 0.05) by season; *: significance < 0.05, n.s.: not significant.

3.5 Comparison of Water Productivity (kg/m^3) in Five Rice Varieties

According to what was previously commented, MA042 and ALM 103 varieties presents the highest productive indexes in the AWD irrigation system, but in most of the varieties evaluated are still lower compared to the same variety under the PF irrigation system. Table 5 shows the comparison of water productivity (kg/m^3) in the five rice varieties evaluated, which were subjected to two irrigations strategies (AWD and PF) during two consecutive seasons. All varieties evaluated, in both seasons, except MA042, showed a decrease in water productivity when switching from the PF to AWD strategy, mainly due to the drastic reduction in yield when changing the irrigation system (Table 4).

Table 5. ANOVA of the difference in water productivity (kg m^{-3}) in five rice varieties, subjected to two irrigation strategies (Alternate Wetting and Drying (AWD) and Permanent Flooding (PF)), for two seasons of field measurements (2017-2018 and 2018-2019)

Variety	Season I (2017-2018)			Season II (2018-2019)		
	AWD	PF	SD	AWD	PF	SD
Zafiro	0.07a	0.75b	*	0.24a	0.52b	*
ALM 103	0.83	1.14	n.s.	0.73	0.94	n.s.
ALM 107	0.57a	1.30b	*	0.39a	0.65b	*
MAO42	1.29	1.17	n.s.	1.18	0.98	n.s.
ALM 112	0.75a	1.44b	*	0.32a	0.80b	*

Note. Different letters between dates indicate statistical differences (SD) between means (Tukey, P ≤ 0.05) by season; *: significance (p < 0.05), n.s.: not significant.

4. Discussion

In the southern hemisphere, the agricultural season extends from October to April depending on the species (summer period) (Figure 1). During this period in the Mediterranean climate of central Chile, the absence of rainfall is common and presents a wide thermal oscillation, that is, a great variation between the daily maximum and minimum temperature. This is mainly due to climate change, which has caused a considerable reduction in rainfall (from 45 to 105 mm over the last 30 years) and an increase in extreme temperatures (IPCC, 2019). This makes rice production complex, especially during the reproductive period, where the plant is subjected to low temperatures that negatively affect its yield, as shown in Figure 1.

According to research conducted by Alvarado (2004), the reproductive stage is one of the most sensitive in rice, where average temperatures below 20 ºC would have a negative effect on the development and viability of the pollen grain, generating greater floral sterility and a greater number of vain grains per unit area. As observed in Figure 1, the minimum temperatures show a significant decrease as of February 20 in both seasons, that is, the intermediate and long cycle varieties reach 50% flowering after this date. Under this same analysis, short-cycle varieties reach 50% flowering before the indicated date (low temperature period), thus reducing the negative effect of low temperatures during the reproductive period of these varieties.

Rice varieties subjected to PF are more correlated with yield variables compared to varieties subjected to AWD. This result is to be expected, since rice needs to maintain a constant water film in order not to reduce its photosynthetic activity (Bouman & Tuong, 2001; Tuong et al., 2005). At the same time, the constant water sheet protects rice from low night temperatures (< 10 ° C) during the primordial onset, microsporogenesis and except for panicle period, avoiding important yield losses due to floral abortion. Regardless of this, among the varieties subjected to AWD, the MA042 variety also presented a highly correlated response with the rice yield component variables, ranking well above the Zafiro variety during the second season (Figure 3). According to some authors AWD generates physiological and biochemical modifications in rice plants (Sun et al., 2012), increasing the metabolic activity of roots (Yang et al., 2017) and increasing the photosynthetic rate of plants (Zhang et al., 2009), which in the cold weather conditions of Chile would not express its maximum potential, due to the low night temperatures recorded in our country. However, MA042, being a short-cycle variety, is more tolerant to low temperatures, mainly because the reproductive period occurs before the low temperatures observed from February 20 (Figure 1), which allows it to express the benefits described above. This same behavior was observed by Jancsó et al. (2007), where short-cycle varieties showed greater tolerance to low temperatures, obtaining higher yields under conditions of water restriction.

An important part of the rice produced in the world is found in subtropical climate conditions, in countries such as China and the Philippines, where the use of alternative irrigation systems such as AWD, produce positive effects both in water savings and increased yields (Cabangon et al., 2004; Bouman et al., 2005; Belder et al., 2004; Sun et al., 2012; Yang et al., 2017). This is because AWD generates physiological and biochemical modifications in the rice plant (Sun et al., 2012), increasing the metabolic activity of roots (Yang et al., 2017) and increasing the photosynthetic rate of the plants (Zhang et al., 2008).

In colder conditions such as the Chilean Mediterranean climate, traditional varieties, such as Zafiro and ALM 112, do not show a good yield, as described by several authors in the literature (Alvarado, 2004; Ortega 2007; Jancsó et al., 2017). This is mainly due to the low temperatures recorded during the reproductive period (Figure 1). As previously mentioned, from February 20 onwards, there is a significant reduction in temperatures, which affect this type of varieties, generating yield losses of more than 50%. This irrigation management strategy negatively affects the grain filling process in long- and intermediate-cycle varieties, limiting the translocation of assimilates due to a lower irrigation input (Pascual & Wang, 2016).

In the case of short-cycle varieties, they show genetic and physiological qualities that keep them hydrated due to their deeper roots, reducing water flow to stem and leaf tissues during the post-anthesis stage. Thus, the application of the AWD strategy significantly increases grain filling rate, due to increased root oxidation activity, increasing the photosynthetic rate of the flag leaf and the activity of enzymes responsible for transforming sucrose into starch during the grain filling stage (Zhang et al., 2008; Sandhu et al., 2019). Thus, MA042 sees its grain yield reduced by only 34% and 4%, while ALM 103 sees it reduced by 57% and 1%, during the first and second seasons, respectively, proving to be better adapted to the lack of irrigation and low temperature environmental conditions. Also, the number of filled grains of this varieties is statistically higher than of varieties such as Zafiro (Table 3), which is greatly affected by lack of water and low temperatures.

Water savings when implementing the AWD strategy were 40% and 42%, for the first and second seasons, respectively (Table 2). This water saving was higher than that registered by Massey et al. (2014), which ranged from 20 to 38% for the comparison of similar irrigation systems. However, yield reduction in traditional variety like Zafiro, was 50% or more, which implies that water productivity decreases. In the case of MA042, yield reduction was only 34% and 4% for each of the study season under study, being lower in percentage terms than the observed water savings. This is also observed to a lesser extent in ALM 103 with a 57% and 1% reduction in yield for each season respectively, but with a smaller reduction and without statistical differences in water productivity. Therefore, both varieties turn out to be more efficient in water consumption and grain productivity, the MA042 variety being superior, however, it presents tended by problems due to the lack of a water sheet. According to Bouman et al. (2005) the current rice varieties, in PF, show a water productivity in relation to evapotranspiration (water used and evaporated) of 0.6 to 1.6 kg m^{-3} of water consumed. All varieties evaluated in

PF fluctuate in this range, several of them being above 1 kg m^{-3} during the first season, while in the case of AWD, only MA042, exceeded 1 kg m^{-3}, approaching and even surpassing the behavior of some varieties under the PF strategy (Bouman et al., 2006).

Finally, it should be noted that regardless of the results found, and the performance achieved by MA042 and ALM103 under intermittent irrigation conditions, it is essential to accompany its production with adequate weed control and fertilization, which supports optimal plant development during reproductive period (Massey et al., 2014).

5. Conclusion

The AWD irrigation strategy in cold Mediterranean weather conditions produces a significant reduction in yield components regardless of the type of variety used, since the buffering effect provided by a 200 mm high water sheet is lost, especially during the reproductive period of the rice crop. Traditional long-cycle varieties, such as Zafiro, are productively unviable under a context of climate change, as they are not able to adapt to a production system with lower water consumption, showing a significantly lower yield than the yield obtained in short-cycle varieties such as MA042 or ALM 103 in this study. Low temperatures (below 10 °C) during the rice reproductive period (after February 20 in this study), produce a significant detrimental effect on the final rice yield, where the number of filled grains/panicle is the most affected component of all. Although short-cycle varieties such as MA042 and ALM 103 also see reduced yields when implementing the AWD strategy, this reduction is less than the water savings obtained, which make this variety an interesting productive option to be implemented by rice producers in cold climates such as Chile, where climate change is increasingly demanding sustainable water management strategies, with water savings of more than 40% in this study. Long-cycle varieties subjected to AWD tend to show a lower productive potential, due to a more stressful environmental condition. According to Bouman (2012) the spikelets that are in the pollination process, when subjected to a water stress condition (water potential < -1.8 MPa) would not open properly, preventing the release of pollen, generating vain grains that would significantly reduce the harvest index of rice. In addition, the low temperatures observed (< 10 °C) would explain the significant drop in yield in this type of rice varieties.

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